

Transient response of dipole antenna using SEM- FDTD method

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Abstract

The transient response of a dipole antenna is investigated using the singularity expansion method (SEM). The required natural modes of the dipole are obtained to good approximation using the finite difference time domain (FDTD) method. In order to generate a certain mode, a plane wave is used to excite the dipole antenna with both a frequency near to the natural dipole mode (resonance) frequency and with a spatial distribution approximating the mode dipole current. The method is applied to a dipole loaded with a resistor, thus the SEM solution is obtained without the need for the dipole impedance in a wide frequency band. The transient response of a dipole is studied for an incident nuclear electromagnetic pulse (NEMP) for dipoles of different lengths, and for an incident short damped sinusoidal plane wave, representing a high power microwave pulse, with different frequencies of the incident wave.

Introduction

Investigation of the transient response of antennas is important in studying EMP effects, high power microwave weapons, localized waves, ultra-wideband communication and radar systems, EMP sensors, ...etc [1-6]. Analysis of the transient response of different types of antennas has been implemented using time domain integral equations (IE), frequency domain IE together with Fourier transform, SEM, FDTD, in addition to high frequency techniques such as time domain physical optics, time domain geometric theory of diffraction and time domain pulsed plane waves [7-12].

The SEM has the advantage that once the antenna natural modes are obtained one can solve different excitation problems in a simple and fast way using a few numbers of natural modes [13]. Such transient problems include exciting the antenna with different waveforms (either as a transmitting antenna or a receiving one) and with different angles of incidence of a plane wave. The solution is particularly simple after the early time period when the incident wave has traversed the antenna.

The natural modes complex frequencies correspond to the resonant modes of the antenna with damping factors accounting for antenna radiation during current oscillation. However, obtaining the natural modes is usually cumbersome, based on solving homogenous integral equations numerically and searching for the complex natural frequencies [14].

In the present work the basic natural modes of the dipole having minimum damping, which are required for solving transient problems [15,16], are obtained in a simple way by using the FDTD method. The modes are obtained by exciting the antenna with a transient plane wave containing a frequency spectrum concentrated near the frequency of the required mode and with a spatial field distribution similar to that of the required mode current. After the transient excitation has died out, the excited antenna oscillates in the intended mode with an exponentially damped sinusoidal waveform, which is used to find the mode complex frequency. By such proper choice of the temporal and spatial distribution of the exciting waveform, each of the resulting modes becomes highly pure, i.e. least contaminated by other modes. This method can be used to simply obtain natural modes of dipoles with loads, which simplifies the solution of the transient problem without the need to have information about the short circuited modes of the antenna and the antenna impedance in a wide frequency band [15].

Once the antenna modes have been obtained, it is straight forward and simple to obtain the transient response of the antenna to different excitation waveforms and different incidence angles. Transient response of dipoles is then investigated for NEMP and short pulse waves resembling high power microwaves with good accuracy.

The SEM method for dipole antennas

The electric field integral equation for the current $I(z)$ on a dipole antenna with exciting electric field E_0 , parallel to the dipole, is [16-18],

$$LI = -s\epsilon_0 E_0 \quad (1)$$

Here L is an operator given by

$$LI = \left[\frac{d^2}{dz^2} - \frac{s^2}{c^2} \right] \int_0^l \frac{\exp(-sR/c)}{4\pi R} I(z') dz' \quad (2)$$

where the dipole occupies $0 < z < l$, s is the laplace transform variable, c is the speed of light, ϵ_0 is the free space permittivity and R is the distance between a current point at z' and an observation point at z on the dipole surface.

For a dipole of length ' l ' and radius ' r ' the antenna parameter Ω is given by

$$\Omega = 2 \ln\left(\frac{l}{r}\right) \quad (3)$$

For a thin dipole with large Ω the asymptotic natural modes currents $I_n(z)$ of the dipole, obtained from the solution of the homogeneous version of equation (1), are sinusoidal, given by [16]

$$I_n(z) = \sin\left(\frac{n\pi z}{l}\right) \quad (4)$$

The complex natural frequencies s_n are given by

$$\begin{aligned} s_n &= J \omega_n - \sigma_n \\ &= J n \pi c/l - \sigma_n \end{aligned} \quad (5)$$

where the damping factors σ_n are proportional to $1/\Omega$ and J is the imaginary unit. For dipoles with Ω which is not large, the complex natural frequencies should be obtained numerically [14,15]. For an incident transient wave on a dipole, the transient excited current on the dipole can be obtained in SEM method mainly in terms of the natural modes of the dipole, with additional polynomial and entire functions of s , whose contributions are usually neglected for dipole antennas [16,19]. The Laplace transform of the excited current is given by [16, 19]

$$I(z, s) = -\epsilon_0 s \sum_n (s - s_n)^{-1} \langle L' I_n, I_n \rangle^{-1} \langle E_i, I_n \rangle I_n \quad (6)$$

where the summation is over the complex frequencies s_n and their complex conjugates, and the operator

$$L' = dL/ds$$

and the scalar product is defined by

$$\langle f, g \rangle \equiv \int_0^l f(z) \cdot g(z) dz \quad (7)$$

Thus

$$I(z, s) = \sum_n \frac{-\epsilon_0 s}{s - s_n} \frac{c_n}{B_n} I_n(z) \quad (8)$$

where c_n is the mode coupling coefficient, given for the thin wire natural modes by

$$c_n = \int_0^l E_z(z, s) I_n(z) dz \quad (9)$$

And B_n is the mode normalization constant

$$\begin{aligned} B_n &= \langle L' I_n, I_n \rangle^{-1} \\ &= \left(\frac{J n \Omega}{4c} \right) \end{aligned} \quad (10)$$

The Laplace transform of the excited current thus takes the form

$$I(z, s) = \frac{4\pi c}{Z_0 \Omega l} \sum_n \frac{s}{s_n (s - s_n)} \left[\int_0^l \sin\left(\frac{n\pi z'}{l}\right) E_z(z', s) dz' \right] \sin\left(\frac{n\pi z}{l}\right) + O(\Omega^{-2}) \quad (11)$$

The dipole current for an incident plane wave with damped sinusoidal time dependence

Consider an incident plane wave with damped sinusoidal time dependence, given by

$$E(t) = 2E_0 \cos(w_k t) e^{-\sigma_k t} \quad (12)$$

where w_k is the radian frequency and σ_k is the damping constant of the incident wave. The Laplace transform of $E(t)$ is (with $E_0=1$)

$$E(s) = \frac{1}{s-a} + \frac{1}{s-a^*} \quad (13)$$

Where $*$ denotes the complex conjugate and

$$a = j w_k - \sigma_k \quad (14)$$

The damped sinusoidal wave can be used to represent an high power microwave signal and can be reduced to the EMP signal.

If the plane wave is obliquely incident on the dipole with an angle θ with the z - axis, the wave front arrives at a point z on the dipole after a time delay

$$T = \frac{z \cos(\theta)}{c} \quad (15)$$

This time shift leads to multiplying the Laplace transform of the incident wave by e^{-sT} , thus

$$E(s) = \left(\frac{1}{s-a} + \frac{1}{s-a^*} \right) e^{-sT} = \sum_{a_i=a, a^*} \frac{e^{-sT}}{s-a_i} \quad (16)$$

The induced current due to E_z , thus equals

$$I(z, s) = \frac{4\pi c}{Z_0 \Omega L} \sin(\theta) \sum_{s_i=s_n, s_n^*} \frac{s I_n(z) < e^{-sT}, I_n >}{s_i (s-s_i)} \sum_{a_i=a, a^*} \frac{1}{s-a_i} \quad (17)$$

To obtain the time dependence of the current, the inverse Laplace transform is performed. By using partial fractions

$$\frac{s}{(s-s_i)(s-a_i)} = \frac{s_i}{(s-s_i)(s_i-a_i)} + \frac{a_i}{(s-a_i)(a_i-s_i)} \quad (18)$$

The required inverse Laplace transform for a general term in eqn.(17) is thus

$$L^{-1} \frac{e^{-sT}}{s-b} = e^{b(t-T)} \quad (19)$$

here $b = s_i$ or a_i , and the response starts at $t=T$. Thus

$$I(z, t) = \frac{4\pi c}{Z_0 \Omega L} \sin(\theta) \sum_{s_i} \frac{I_i(z)}{s_i} \sum_{a_j} \left[\frac{s_i < e^{s_i(t-T)}, I_i >}{s_i - a_j} + \frac{a_j < e^{a_j(t-T)}, I_i >}{a_j - s_i} \right] \quad (20)$$

Defining

$$f_n(b) = \int_0^t e^{-bT} \sin \frac{n\pi z}{l} dz \quad (21)$$

where T is a function of z given by eqn.(15), then

$$f_n(b) = \left[\frac{e^{-b \frac{\cos(\theta)z}{c} + A_n} - 1}{-b \cos(\theta)/c + A_n} \right] - \left[\frac{e^{-b \frac{\cos(\theta)z}{c} - A_n} - 1}{-b \frac{\cos(\theta)}{c} - A_n} \right] / (2J) \quad (22)$$

where $A_n = j \frac{n\pi}{l}$. The coupling coefficient function in eqn.(21) is not a function of s (type 1) [22]. For an

incident field of amplitude E_0 in eqn.(12) rather than $2E_0$, eqn.(20) reduces to

$$I(z, t) = \frac{2\pi c E_0}{Z_0 \Omega L} \sin(\theta) \sum_{s_i=s_n, s_n^*} I_i(z) \sum_{a_j=a, a^*} \left[\frac{e^{s_i t}}{s_i - a_j} f_i(s_i) + a_j \frac{e^{a_j t}}{s_i (a_j - s_i)} f_i(a_j) \right] \quad (23)$$

The exponential terms including s , represent natural oscillations of the dipole, whereas those including a , represent forced oscillations.

Calculating the natural modes of the loaded dipole using FDTD Method

The FDTD method is used to find both the natural dipole modes with a resistive load and also to check the dipole current for an incident transient plane wave. The conventional Yee algorithm is used to obtain the scattered field in free space [9, 10]. Liao absorbing boundary conditions are used to enclose the computation domain.

FDTD equations at a cell with a lumped resistor

We consider a dipole antenna loaded with a resistor R . The FDTD updating equations at the cell with a lumped resistor R , oriented in the z - direction, can be obtained by relating the current density j_z flowing in R to the total parallel electric field in the cell using Ampere's curl equation for the total field [20]

$$\nabla \times H_z = \epsilon \frac{\partial E_z}{\partial t} + j \quad (24)$$

The total field is the sum of the incident field E_i and the scattered field E_s at a cell (i, j, k) , for example

$$E_z(i, j, k) = E_i(i, j, k) + E_s(i, j, k) \quad (25)$$

In order to obtain the equation for the scattered field one considers the equation of the incident field.

$$\nabla \times H_z = \epsilon \frac{\partial E_i}{\partial t} \quad (26)$$

By eliminating the incident field from equation (24) one obtains for the scattered field

$$\frac{\partial E_s}{\partial t} = (\nabla \times H_s - j_z) \frac{1}{\epsilon} \quad (27)$$

whose finite difference form reads for the component E_z at time step $n+1$ (with subscript 's' omitted),

$$\frac{E_z^{n+1}(i, j, k) - E_z^n(i, j, k)}{\Delta t} = \frac{1}{\epsilon} \left(\frac{H_y^{n+\frac{1}{2}}(i, j, k) - H_y^{n+\frac{1}{2}}(i-1, j, k)}{\Delta x} - \frac{H_x^{n+\frac{1}{2}}(i, j, k) - H_x^{n+\frac{1}{2}}(i, j-1, k)}{\Delta y} - \frac{I_z^{n+\frac{1}{2}}(i, j, k)}{\Delta x \Delta y} \right) \quad (28)$$

where $j_z = I/A$ and I is the total current evaluated at time step $(n+0.5)$, similar to the magnetic field, $\Delta x, \Delta y, \Delta z, \Delta t$ are the spatial and temporal steps (spatial steps are equal) and A is the cross sectional area

$A = \Delta x \cdot \Delta y$

By expressing the current in terms of the voltage

$$I^{n+0.5} = V/R = \Delta z E_z^{n+0.5} / R \quad (29)$$

The value of the electric field at time step $n+0.5$ may be obtained as the average of the values at time steps n and $n+1$ at which the electric field is calculated, thus

$$\frac{E_z^{n+1}(i, j, k) - E_z^n(i, j, k)}{\Delta t} = \frac{1}{\epsilon} \left[\frac{H_y^{n+0.5}(i, j, k) - H_y^{n+0.5}(i-1, j, k)}{\Delta x} - \frac{H_x^{n+0.5}(i, j, k) - H_x^{n+0.5}(i, j-1, k)}{\Delta y} - \Delta z \left(\frac{E_i^{n+1}(i, j, k) + E_i^n(i, j, k)}{2R\Delta x \Delta y} + \frac{E_z^{n+1}(i, j, k) + E_z^n(i, j, k)}{2R\Delta x \Delta y} \right) \right] \quad (30)$$

Or

$$E_z^{n+1}(i, j, k) \left[1 + \frac{\Delta z \Delta t}{\epsilon 2 R \Delta z \Delta y} \right] = E_z^n(i, j, k) \left[1 - \frac{\Delta z \Delta t}{\epsilon 2 R \Delta x \Delta y} \right] + \frac{\Delta t}{\epsilon \Delta x} [H_y(i, j, k) - H_y(i-1, j, k)] - \frac{\Delta t}{\epsilon \Delta y} [H_x(i, j, k) - H_x(i, j-1, k)] - \frac{\Delta z \Delta t}{2 \epsilon R \Delta x \Delta y} [E_i(i, j, k)^{n+1} + E_i(i, j, k)^n] \quad (31)$$

Excitation of the natural modes of the dipole

The natural damped sinusoidal modes of the dipole take the form

$$I_n(t) = i_0 \cos(\omega_n t) \exp(-\sigma_n t) \quad (32)$$

Where ω_n and σ_n are represented in eqn.(5). The main modes required for the SEM solution are the least damped modes [15]. Other natural modes exist with higher damping factors, but such modes are not relevant in the SEM.

To excite a certain mode on the dipole, a plane wave is used to excite the dipole with approximate frequency and spatial distribution of field along the dipole as the mode current required to be excited

$$E_i = E_0 \sin(\Pi Z \frac{n}{l}) \sin(\omega_n t) \sin(\omega_n t / 8) \quad (33)$$

Where n is the mode number. In order to limit the period of the incident plane wave, a few cycles of the natural frequency ω_n are used, modulated by a half sine wave of a lower frequency (1/8 in eqn.33), Fig.(1a), in order to make the field continuous with time, thus the spectrum of this wave becomes concentrated around ω_n , so the other natural modes are only negligibly excited. After the termination of this excitation, the current oscillates on the dipole mainly with the intended natural mode. The complex frequency of the mode is calculated by considering the successive positive and negative maxima P_i and P_{i+1} in the damped sinusoidal current waveform and calculating the damping factor (σ_n) and frequency f_n of the mode as

$$f_n = \frac{1}{2m\Delta t} \quad (34)$$

$$\sigma_n = \frac{\ln P_i - \ln P_{i+1}}{m\Delta t} \quad (35)$$

Where m is the number of time steps Δt between such two successive peaks.

Results and discussion

The natural modes of the dipole

The short circuited dipole

Fig(1b) shows the variation of the excited current, at the center of a short circuited dipole, with time, where the frequency of the incident plane wave is nearly equal to the frequency of the first natural mode, eqn.(5), $n=1$, and the direction of the incident plane wave is normal to the dipole axis. The forced excitation due to the incident wave terminates after 4 cycle then the damped oscillation of the first natural mode begins. The dipole used is a strip dipole of rectangular cross section with thickness to width ratio of 1/3 which is equivalent to a cylindrical dipole of radius to width ratio of 0.38 [21]. The dipole is 39 cells long and 3 cells wide, thus its equivalent radius is 1.14 cells (thus the corresponding $\Omega = 7$). The actual used frequency is 6 GHz, with $\Delta x=0.000625m$ and $\Delta t=1.2*10^{-12}$ sec. This time step equals the cell length divided by $c*\sqrt{3}$ to satisfy the stability condition [9,10]. A load of 1 Ohm is used in place of the short circuit to avoid overflow in the computations, eqn.(31).

Fig (2a) show the current distribution of the first mode on the dipole, which is seen to be nearly sinusoidal. Fig (2b) shows also the current distribution of the third mode which is also nearly sinusoidal, showing nearly no contamination by the first or fifth modes (which have even current distributions w.r.t. the dipole center). The even numbered modes contain an even number of half sine waves and have zero current at the center of the dipole.

Table (1) shows the computed damping factors and natural frequencies (rad/sec) of the first 5 modes, normalized w.r.t. twice the nominal first resonance frequency of the dipole (c/l). Comparison is made with the results of [15]. The comparison shows reasonable agreement, particularly for ω_n , with the deviations expected to be due to slight contamination by the other natural modes and the small difference of the dipole parameters Ω of the 2 compared cases.

Table 1. Comparison of computed modes normalized complex frequencies with those of Ref. 15

n	Calculated, $\Omega = 7$		Ref. 15, $\Omega = 8$	
	w(l/c)	$\sigma(l/c)$	w(l/c)	$\sigma(l/c)$
1	2.58	0.279	2.77	0.334
2	5.6	0.55	5.748	0.46
3	8.38	0.65	8.7	0.603
4	12.84	0.825	11.74	0.684
5	14.5	0.875	14.75	0.774

Dipole with 75 Ohm load

Fig(3a) shows the current distribution of the first mode for the dipole loaded with 75 Ohm. Fig (3b) shows the current distribution of the third mode. A slight dip can be seen in the current at the dipole center due to the 75 Ohm load.

Table (2) shows the calculated damping factors and natural frequencies. The damping factors are higher for the odd numbered modes for the 75 Ohm case than for the 1 Ohm case (table 1) due to mode attenuation by the resistive load. On the other hand, for the even numbered modes the damping factors are nearly the same since the current is zero at the dipole center for these modes, thus the damping is not affected by the presence of the load.

Table (2) The modes normalized damping factors and radian frequencies a for dipole loaded with 75 Ohm

mode number n	damping factor, $\sigma(l/c)$	Frequency, w(l/c)
1	0.69	2.65
2	0.55	5.65
3	1.18	8.38
4	0.85	11.15
5	1.54	14.6

Dipole response to an incident NEMP

An NEMP can be approximated by the double exponential waveform [15], [2]

$$E = E_0 (e^{-\alpha t} - e^{-\beta t}) \quad (36)$$

where $\alpha = 1.6 \cdot 10^6 \text{ sec}^{-1}$, $\beta = 2.6 \cdot 10^8 \text{ sec}^{-1}$

β Corresponds approximately to the inverse of the rise time constant, and α corresponds approximately to the inverse of the decay time constant, and E_0 equal approximately $5 \cdot 10^5 \text{ V/m}$ for NEMP. The laplace transform of E is

$$E(s)/E_0 = \frac{1}{s + \alpha} - \frac{1}{s + \beta} \quad (37)$$

Each of the two exponential factors can be considered as a special case of a damped sinusoid with zero frequency, eqns. (12, 13).

Fig.(4a) shows the computed transient current in a short circuited (1 Ohm) dipole of length 2 meter (75MHz resonance frequency) due to an NEMP normally incident on the dipole axis. In this case the even natural modes are not excited. Three odd modes are used in the calculations, which are enough to get good accuracy at relatively late time. The main excited mode is the first mode. Figure (4b) shows the computed response using an equation of Ref. 15 corresponding to eqn.(23), with the exact modes resonance frequencies and damping coefficient taken from [15] (table1). Fig.(4c) shows the computations of the excited current using FDTD method for an incident NEMP. The comparison shows good agreement of the 3 results.

Loaded dipole

The more practical case of a dipole loaded with 75 ohm is then considered. Fig (5a) shows the transient current for dipoles of different lengths resonating at different frequencies. It can be seen that the dipole current decreases as its resonance frequency increases. At high dipole resonance frequencies, Fig.(5c,d), the weak forced excitation by the double exponential NEMP waveform begins to dominate the current natural oscillations. The decrease of the current may be attributed to both the decrease of the effective dipole length (by 100-times from 10MHz to 1GHz) and the decay of EMP spectrum, Fig.(6), eqn.(37), by approximately the same order of magnitude. The damping of the current due to the load can be seen by comparing Fig.(4a) and Fig.(5b). By using the loaded dipole natural modes, one does not need to have both the short circuited dipole modes and

the dipole impedance data in a wide frequency range and does not need to use numerical inversion of Laplace transform as done in Ref.15.

Incident damped sinusoidal plane wave

High power microwave weapons use few cycles of microwave frequency in order to penetrate devices operating at microwave frequencies. Here we use a damped sinusoidal incident plane wave to investigate such conditions. In order to investigate dipole response to an incident plane wave of short period (wide spectrum), we use a large damping constant $\sigma_k = 1.9 \times 10^{10}$, which equals the inverse of the damping time constant of the sinusoidal wave envelope. If the frequency of the sinusoid is low, the high damping constant makes the waveform to be nearly an impulse.

A dipole of length 2.5 cm (nominally resonating near 6GHz) is considered with incident plane waves of different frequencies ($f_k = 1\text{GHz}, 5\text{GHz}, 10\text{GHz}, 15\text{GHz}$), normally incident on the dipole axis. Fig.(7) shows the dipole responses. In Figs.(7a,b), with $f_k = 1$ and 5 GHz, the first natural mode of the dipole is excited. However, in Fig.(7b), the second and third peaks are higher than in Fig.(7a) since the frequency of the incident wave is near the dipole resonance frequency. In Figs.(7c,d), ($f_k = 10\text{GHz}, 15\text{GHz}$), contributions of the third natural mode are noticed, particularly in Fig.(7d). It can be seen that the peak amplitude of the excited current varies slightly with changing the frequency of the incident wave. This can be attributed to the wide spectrum of the short period incident wave shown in Fig.(8), eqn.13. The peak excited current in a dipole is thus expected to be mainly proportional to its length when a short high power microwave pulse (with wide spectrum) is incident on the dipole.

The response is computed for $t > l \cos\theta / 2c$, when the wave arrives at the dipole center. The peak of the current is less than that of Fig.7b and the second natural mode (with odd spatial distribution w.r.t. the dipole center) also contributes to the current (not shown at dipole center). Both of the effects are due to the inclined angle of incidence of the wave.

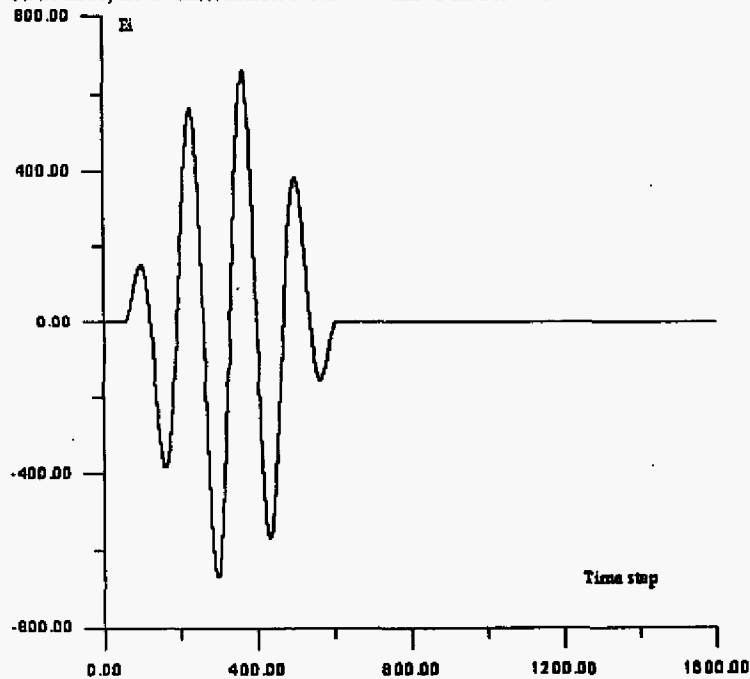
Conclusion

The computationally efficient SEM method is used to investigate the transient response of dipole antennas using the natural complex frequencies of the dipole. A FDTD approach is used to simply obtain the approximate complex natural modes of the dipole. The modes are obtained for a dipole loaded with a resistor, thus the solution of the transient problem does not require the dipole impedance to be known in a wide frequency range. The obtained natural modes are used to find the response of dipoles of different lengths to the NEMP. The excited current decays sharply as the dipole resonance frequency increases due to the decaying spectrum of the NEMP with frequency and the shorter effective length of the dipole. The response of a dipole to a highly damped sinusoidal plane wave (resembling high power microwave pulse) is obtained. The peak excited current in the dipole changes slightly with the main frequency of the incident wave due to its wide spectrum caused by its sharp damping.

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Fig(1-a)The incident waveform

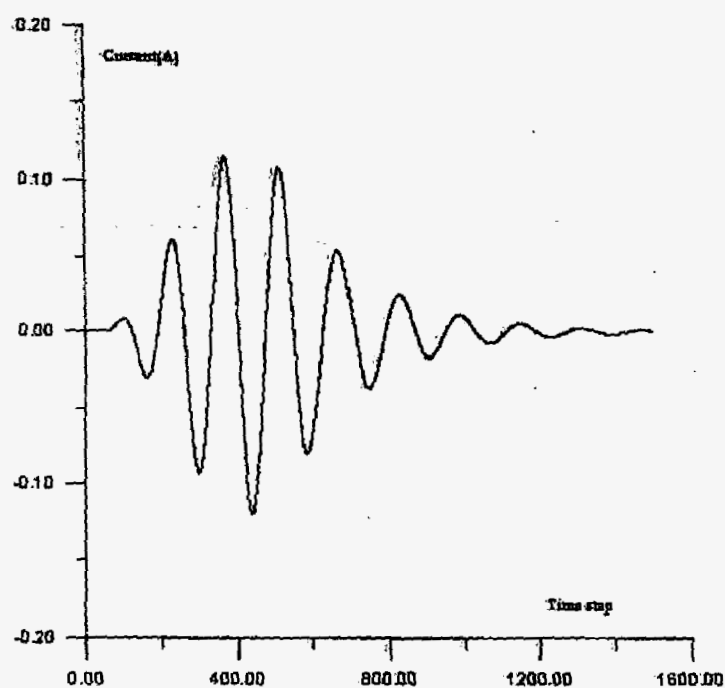


Fig.(1-b) The current at the center of a short circuited dipole versus time when excited by a plane wave with the waveform of Fig.(1a)

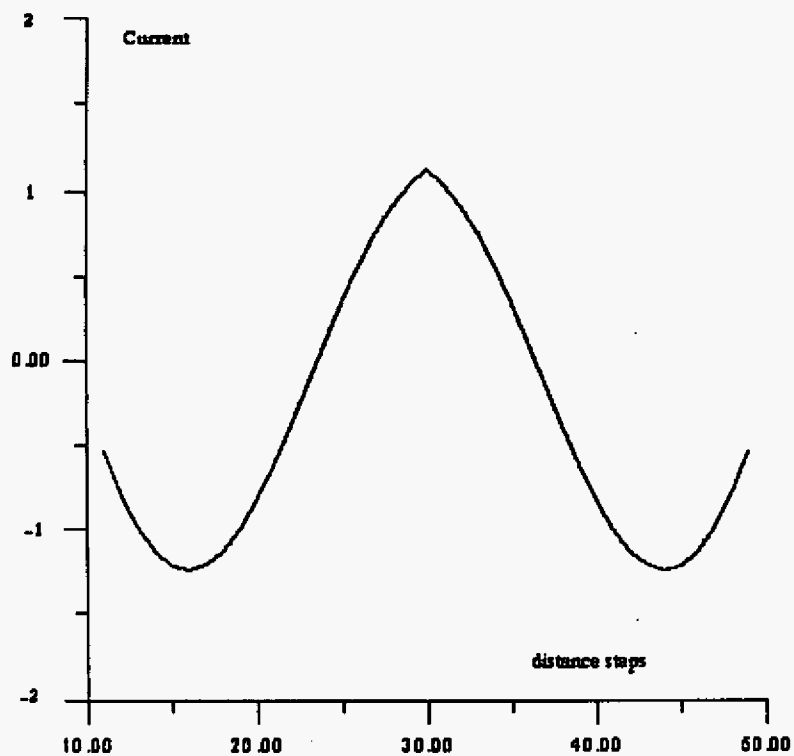


Fig (2-b) The current distribution of the third mode
The current distribution of the first mode on the
Short circuited dipole (the dipole occupies the cells from

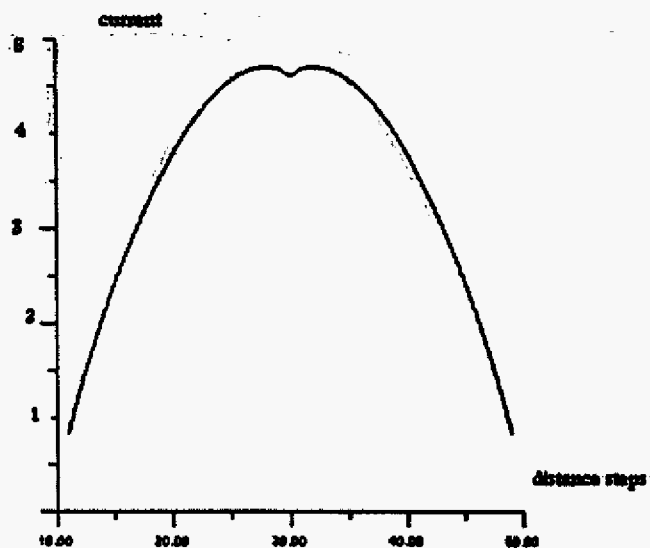


Fig.(3-a) The current distribution of the first mode on the dipole loaded by 75 Ohm

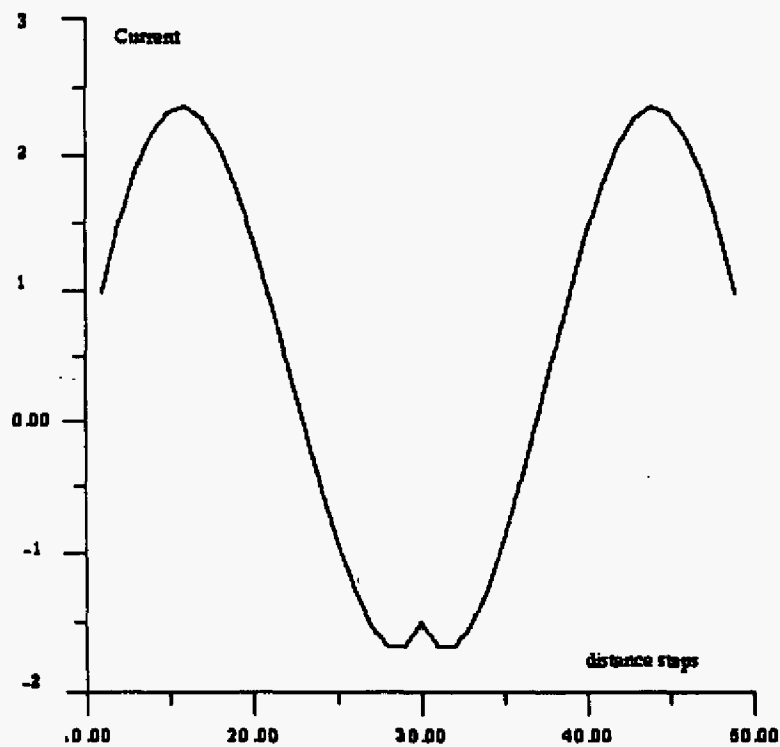


Fig.(3b) The current distribution of the third mode on the dipole loaded by 75 ohm

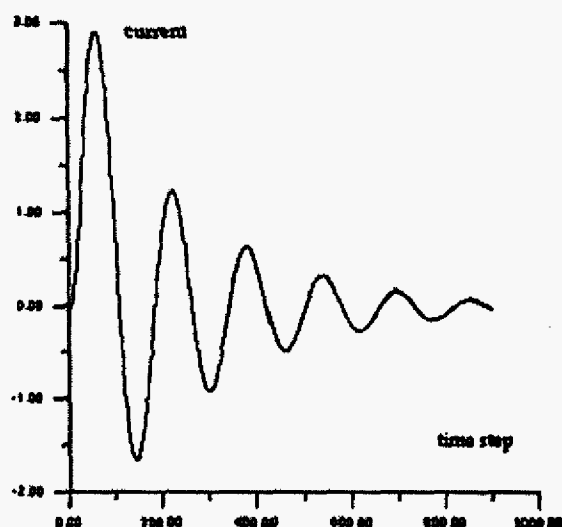


Fig. (4) Transient current (Amp) induced at the center of a short circuited dipole of length 2 m (nominal resonance frequency of 75MHz) with an incident NEMP ($E_0=1000$, $\Delta t=10^{-10}$ sec.)
a) Computed (1 Ohm load)

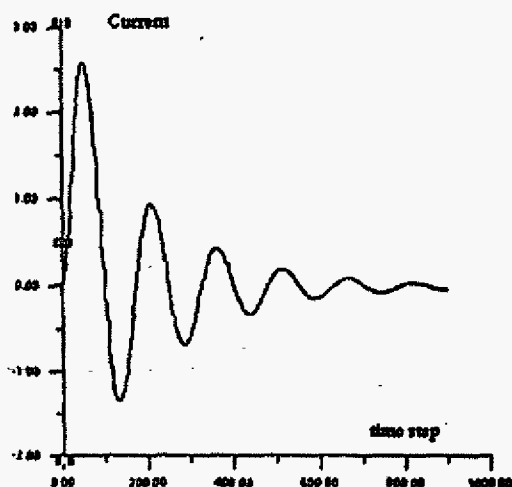


Fig.(4 -b) Results based on Ref. 15, 0 Ohm

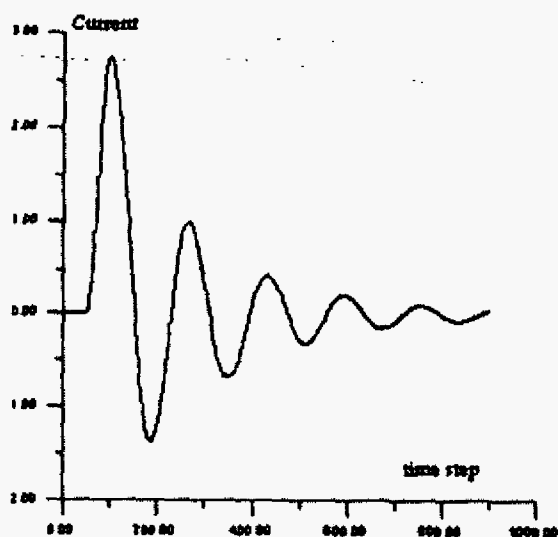


Fig.(4-c) FDTD results, 1 Ohm load

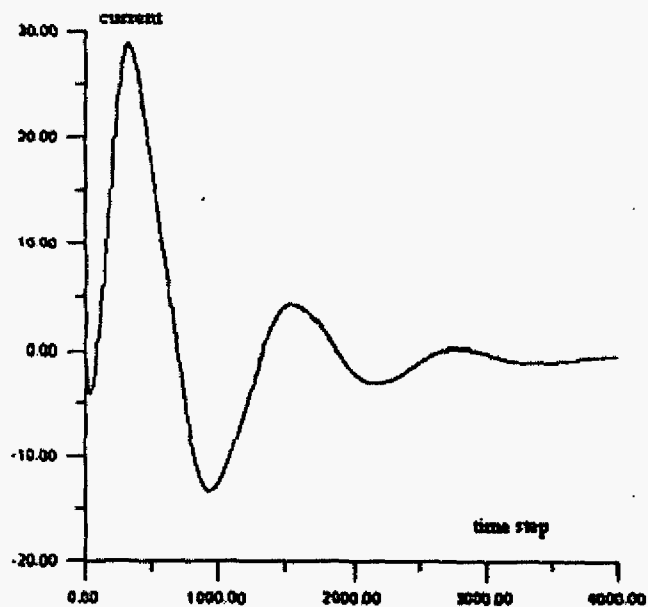


Fig.(5-a) Computed transient current (Amp) at the center of a loaded dipole with 75 Ohm due to NEMP ($E_0=1000\text{V/m}$, $\Delta t=10^{-10}\text{sec}$.)a) dipole of nominal resonance frequency of 10MHz

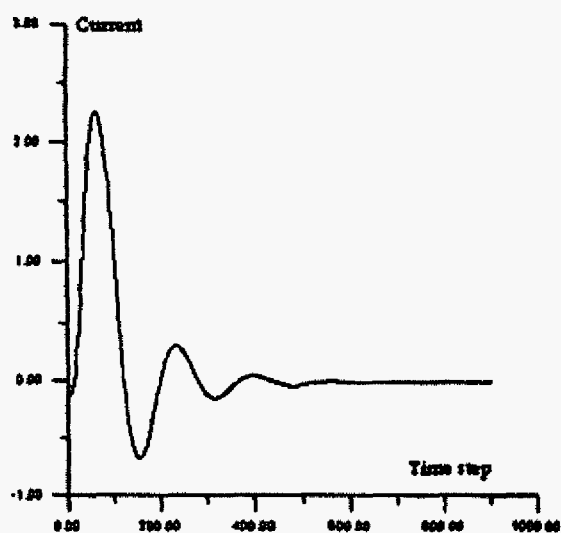


Fig.(5-b) Dipole of nominal resonance
Frequency of 75MHz

90

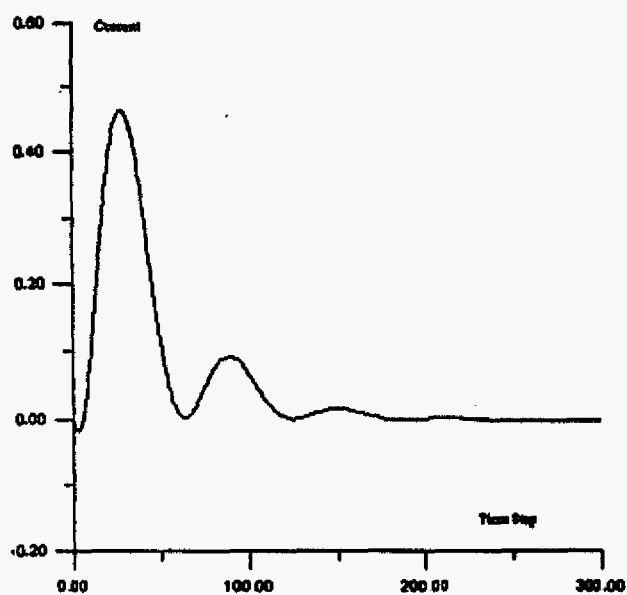


Fig.(5-c) Dipole of nominal resonance frequency of 200MHz

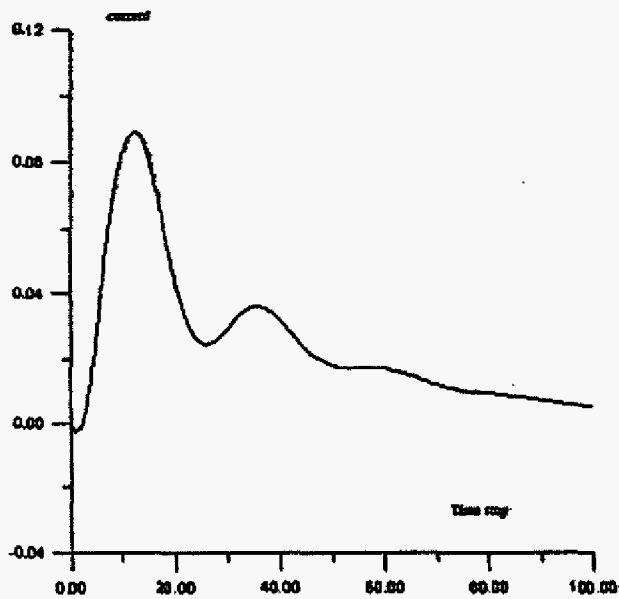


Fig.(5-d) dipole of nominal resonance frequency of 500MHz

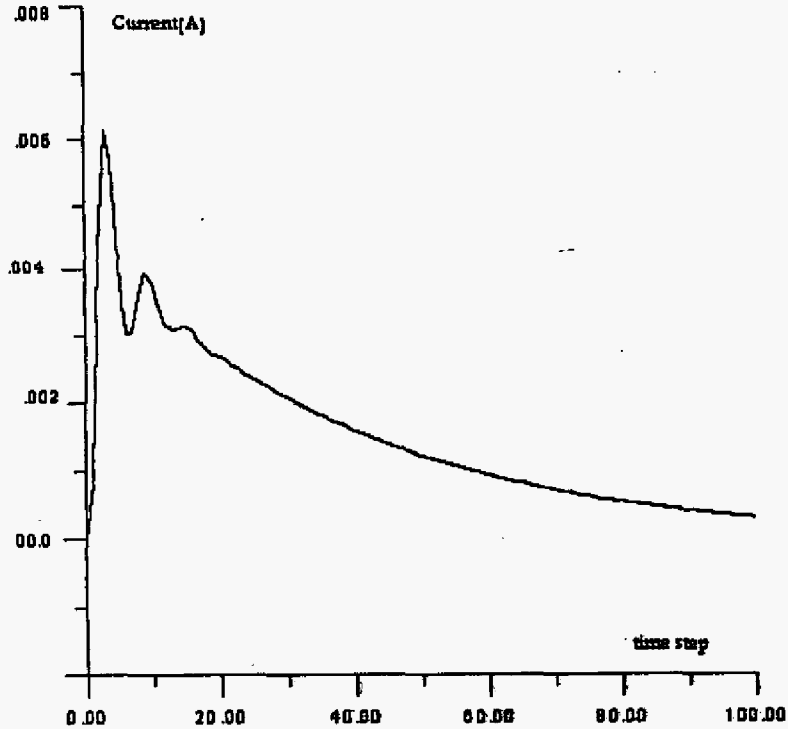


Fig.(5e) Dipole of nominal resonance frequency of 2GHz

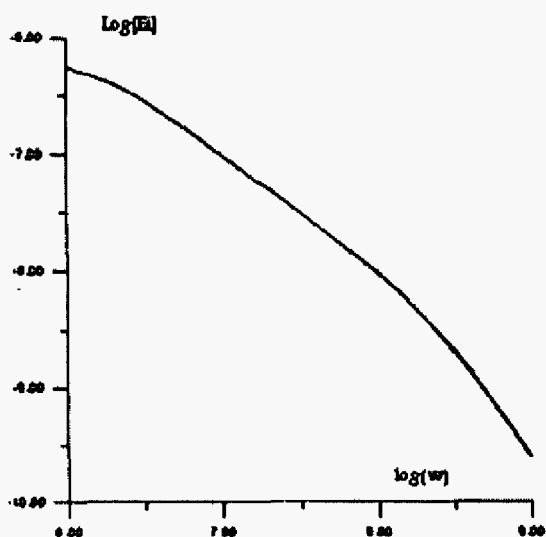


Fig (6) NEMP spectrum (log-log scale)

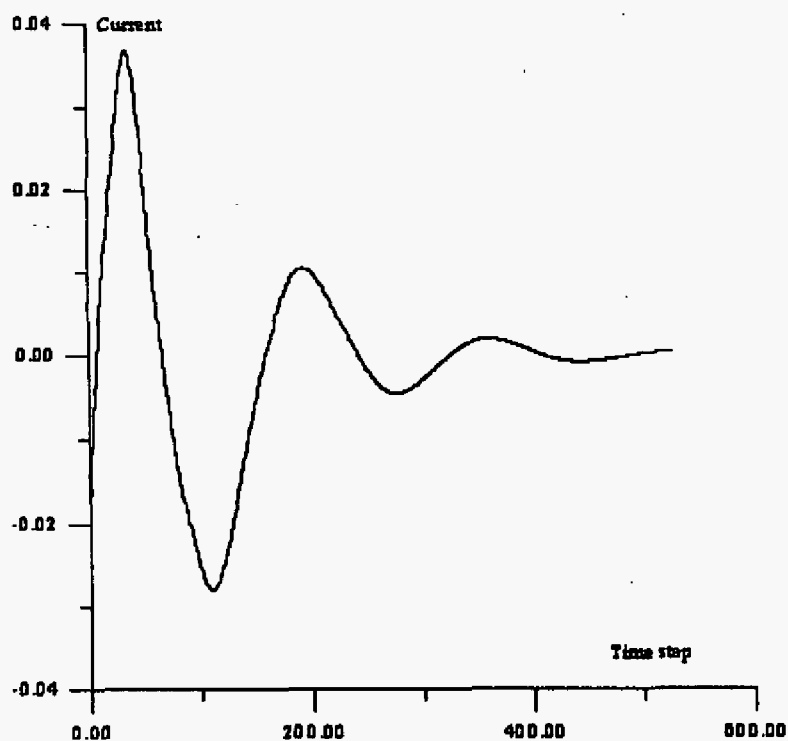


Fig.(7) Computed transient current (Amp) at the center of a dipole of length 2.5cm loaded with 75 Ohm due to a damped sinusoidal wave ($E_0=1000\text{V/m}$, $\Delta t=1.2 \times 10^{-12}\text{sec.}$)
a) $f_k=1\text{GHz}$

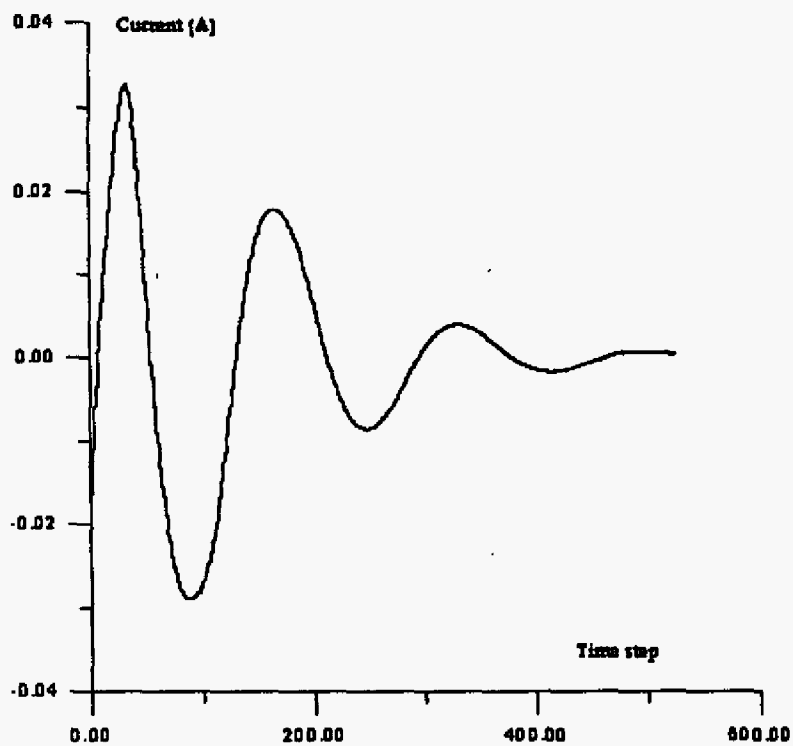
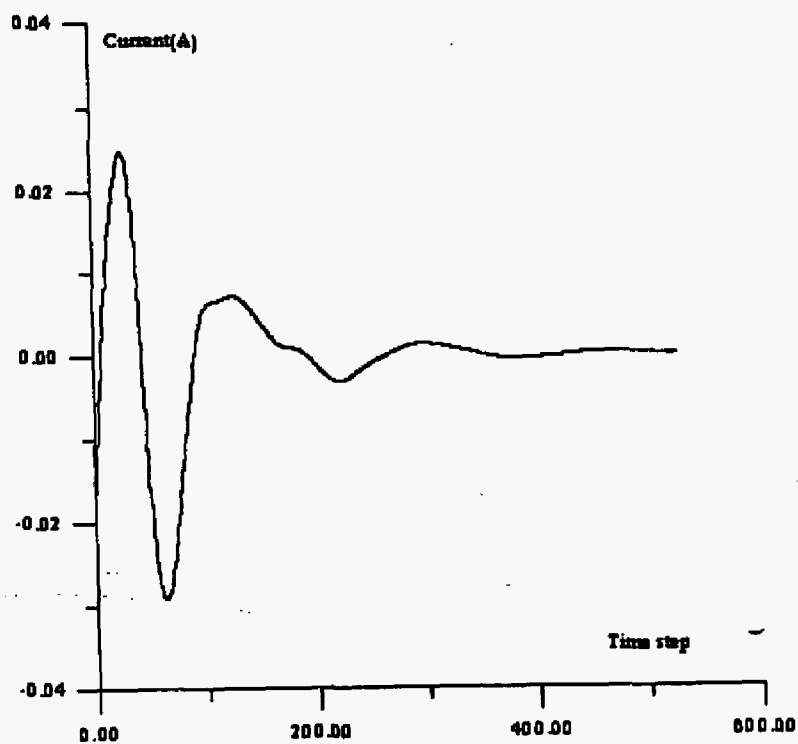


Fig.(7b) $f_k=5\text{GHz}$



Fig(7-c)

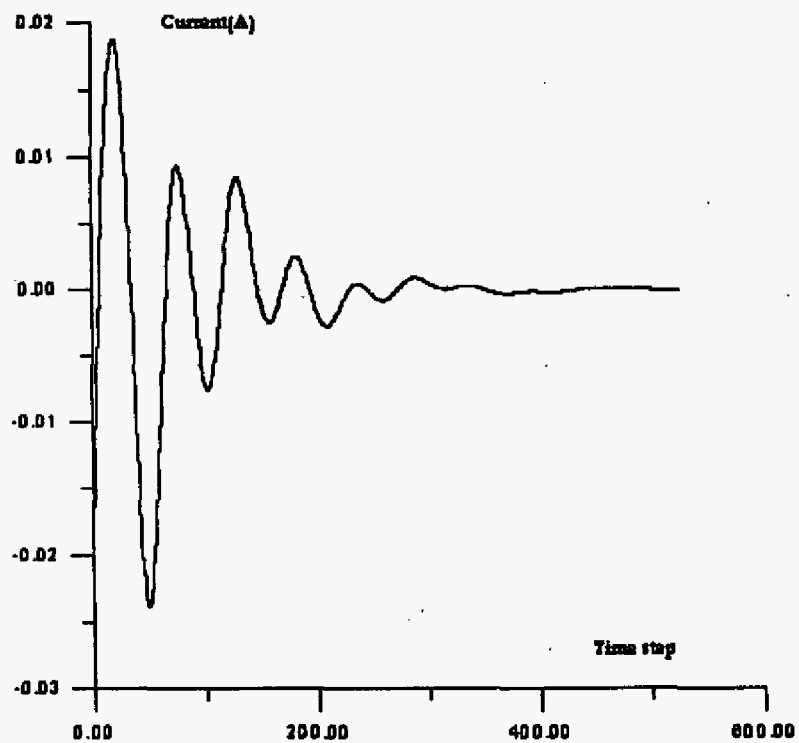


Fig.(7d) $f_k=15\text{GHz}$

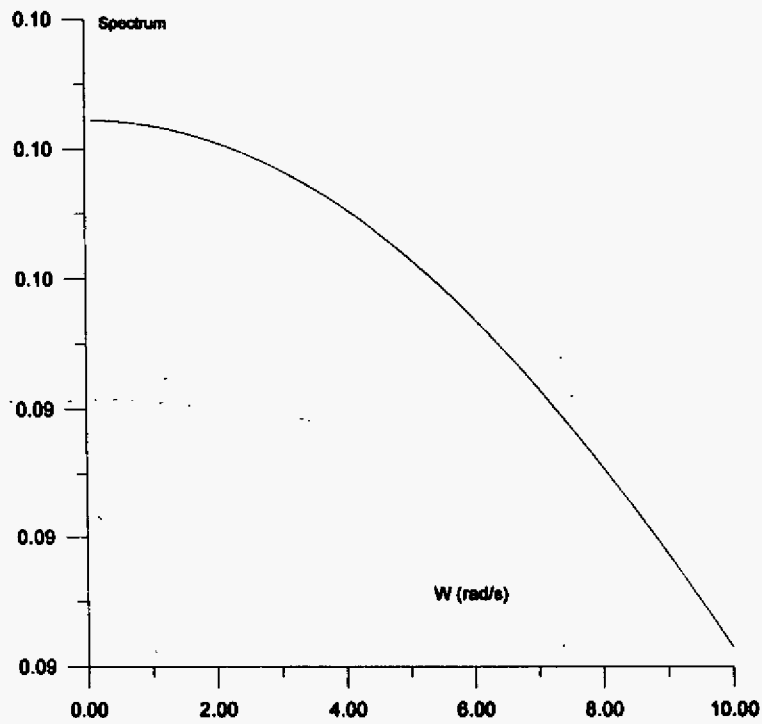
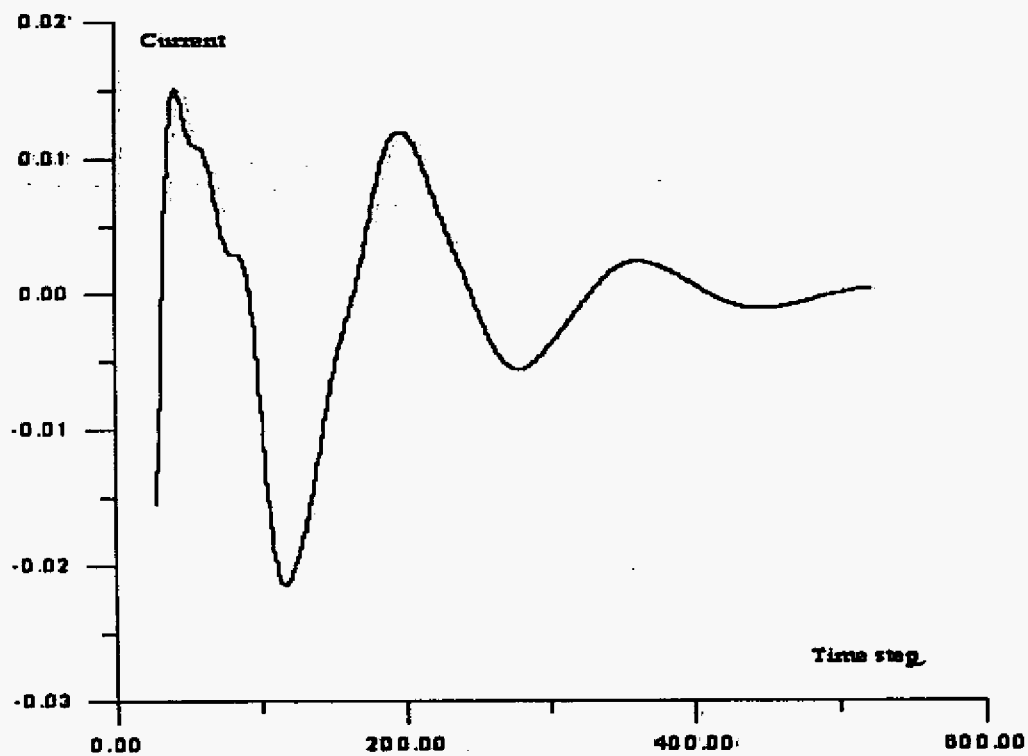


Fig.(8) Damped sinusoid spectrum, linear scale
($f_k = 5\text{GHz}$, $\sigma_k = 1.9 \times 10^{10}$)



fig(9)